A method for detecting the presence of radar signal emitters, an Electronic Support Measures unit and a system for determining the position and identity of said emitters.

Field of the invention

Radar ESM systems are used to detect and identify radars present in an area, by determining the direction of arrival, and emitter characterization of radar pulses.

Technical Background

Such systems include a receiver covering the pertinent radar frequencies. The receiver needs to cover a wide radar frequency band (typical 2-18 GHz) with 360° of angular coverage. At the same time, the system must perform thorough analysis of each received pulse in order to identify radar emitters. The system should be man-portable in field, and should be able to operate with battery power. Multiple systems should be able to find emitter position (both bearing and range).

Three main solutions are known:

Wide bandwidth crystal receiver

A crystal receiver may be used to cover the entire bandwidth. This receiver detects the signal envelope, and coarse pulse parameters may be measured. At least four such receivers are needed to achieve an angular coverage of 360°.

The wide bandwidth crystal receiver is capable to perform coarse pulse analysis only. Important pulse parameters such as carrier frequency and frequency or phase modulation are lost. Thus emitter characterization is coarse at best. In a scenario with multiple emitters, the use of two or more ESM-receivers at different locations to position the target emitter may fail since emitters received in one receiver

may be associated with a different emitter received in other receivers.

Parallel receivers

Multiple receivers are used to cover the entire bandwidth. With current technology, approximately 20 parallel receivers may be used to divide the entire bandwidth into sub-GHz channels, which in turn may be processed with current digital processors. In order to cover 360°, at least 4 such receiver packs with the antennas pointing in different directions are needed to perform direction finding.

The parallel receiver solution performs high quality pulse measurement, and may therefore be used for emitter characterization. Determining emitter position may be performed when two or more receivers at different locations are used, since each pulse and each emitter may be identified. On the other hand, this solution requires massive parallelism in both radio hardware and processing hardware. The result is high weight and very high power consumption rendering this concept useless for man-portable operation.

Scanning receivers

In order to perform detailed pulse analysis, a single narrowband receiver may be used for each antenna direction. The receiver is used to scan the entire frequency bandwidth sequentially. Detailed pulse analysis may be performed within the narrow instantaneous bandwidth.

The scanning receiver may be built as a compact unit with low power consumption, and may also provide detailed pulse measurement. The problem with this receiver configuration is the low probability of intercept due to low instantaneous bandwidth. Radars operating with single scan policy will most probably not be detected.

Brief summary of the Invention

It is an object of the present invention to provide an ESM system for detecting the presence of radars in an area that covers an adequate instantaneous bandwidth and is able to perform a detailed pulse analysis in order to identify the emitter source.

Another object is to provide a system with the above features while being light in weight and power efficient.

These objects are met by a method, an Electronic Support Measures unit and a system according to the present invention as covered by the appended patent claims.

Brief description of the drawings

The invention will now be described in detail in reference to the appended drawings, in which:

Fig. 1 shows a number of ESM-units according to the present invention in use; multiple ESM-sensors are networked for determining the posistion of a radar emitter, using a common emitter database for recognition,

Fig. 2 shows the physical design of a prototype receiver,

Fig. 3 is an overview of a system according to the present invention,

Fig. 4 shows the frequency band splitting and down conversion scheme used in the inventive system,

Fig. 5 is a block diagram of the receiver front end,

Fig. 6 is a block diagram of the receiver's second stage,

Fig. 7 is a diagram showing the Fourier transform of a received pulse; used for calculating the carrier frequency of a radar emitter,

Fig. 8 is a diagram showing a pulse from a radar emitter; used for calculating the pulse width,

Fig. 9 is a diagram showing the gain of three different antennas; used for calculating Direction of Arrival based on pre-calculated antenna lobe calibration function,

Fig. 10 shows received pulses plotted in a DOA/frequency-diagram,

Fig. 11 shows the pulses received from a radar emitter; used for measuring emitter antenna beam-width and rotation time.

Detailed description of the invention

Fig. 1 shows a typical setup for an ESM receiver system. A number of ESM-units 1 - 4 are placed in the terrain along a coastline. Each ESM-unit is adapted to receive and analyse signals emitted by radars present in the surrounding area. In this case a tanker 5 is sailing along the coast, while its radar is constantly scanning the horizon. Each ESM-unit 1 - 4 receives the radar signals, resolves the direction of arrival and identifies the signature. The ESM-units are connected in a network. Said network includes a control center 6. In the control center, the data received from the ESM-units 1 - 4 are compared and analysed in order to find the position of the radar source (tanker 5) and its identity (based on the signature of the radar pulses and a database of known signatures).

Each ESM-unit 1 - 4 includes a number of antennas pointing in different directions, receivers and signal processing circuitry. Each antenna is covering a sector of the surrounding area, and the total assembly is covering the whole horizon.

The Receiver Unit

The physical design of a prototype ESM-unit according to the present invention is shown in Figure 2. 12 antenna

elements are used to cover 2 to 18 GHz in 6 directions. In each direction two antennas are used; the lower large antenna covering the frequency band of 2 - 6 GHz, while the small upper antenna covers 6 - 18 GHz.

The ESM-unit or receiver system consists of two units, namely: The Receiver unit 7 (Antenna, Receiver and Navigation sub-unit) and the Processing Unit 8 as shown in figure 3.

The antennas 10a, b - 16a, b are delivering their signals to the receiver unit 7. In the receiver unit 7 the signals from each of the upper antennas 10a - 16a are split into three 4 GHz wide sub-bands, i.e. a 6 - 10 GHz sub-band, a 10 - 14 GHz sub-band, and a 14 - 18 GHz sub-band. The three sub-bands together with the 2 - 6 GHz sub-band from the lower antenna are converted into a single intermediate frequency (IF). There is one IF channel for each antenna set, i.e. a total of six IF channels. IF channels of opposing antennas are combined into one channel (not shown in the figures); thus providing a total of three IF channels.

In the receiver's second stage, Figure 6, the 4 GHz IF is again split into four 1 GHz wide sub-bands, which are further down-converted and combined into baseband channels of 1 GHz bandwidth. Thereafter the signals are sent to the processing unit 8 for digitalization and processing. The conversion scheme is detailed in Fig. 4.

In addition to the antenna/receiver chain, this unit contain an attitude determination unit (compass) 18 and a GPS antenna 17. All is contained within a single unit that may be mounted either on a tripod or fixed on an antenna mast.

Radio design

The receiver front-end is shown in Figure 5. The Ant Lo input receives the signal from one of the lower antennas 10b - 16b, while Ant Hi in receives the signal from the upper antenna 10a - 16a. The signals are filtered in band-pass filters 20a - 20d, whereupon the signal from the upper antenna is split into three sub-bands. The signals from the band-pass filters are amplified in low-noise preamplifiers 21a - 21d and fed to mixers 22a - 22d. In the mixers 22a - 22d, the signals are downconverted to IF channels of identical frequency range and filtered in another set of band-pass filters 23a - 23d. The outputs from the IF-filters 23a - 23d are combined in an adder 25.

Signal from each sub-band are thus overlaid each other. Since the signals are pulsed, the probability of simultaneous signal from different channels is quite low.

In order to determine direction and frequency of incoming pulses, broadband pulse detection is performed in each of the original channels before combining. For this end, four detectors 24a - 24d are included, one in each IF channel. The outputs from the detectors are fed to a comparator 26, for identifying which channel a given signal occurs in.

The second stage of the receiver is shown in Figure 6. Again, the first IF signal received from the front- end in Figure 5 is split into four sub-bands in band-pass filters 27a - 27d, amplified in amplifiers 28a - 28d, down-converted in mixers 29a - 29d, filtered in band-pass filters 30a - 30d and combined in adder 32. The resulting baseband channel in the range 0 - 1 GHz has a bandwidth matched to the A/D converters in the subsequent processing system (typical 1GHz with 2.5 GS/s A/D converters).

In addition a oscillator and control block (not shown) is needed to generate all oscillator frequencies, control

signals to the amplifiers and handle trigger signals from each of the channels.

The resulting channels are narrow enough for A/D conversion, and the pulses may be processed with one single processor. The necessary number of parallel A/D converters is equal to half the number of antenna directions (typical three with six antenna directions).

The Processing Unit

A four-channel 1GS/s A/D converter is used for digitalisation of the receiver channels. A GPS receiver is used for position determination, and the compass in the Antenna unit is read for antenna attitude determination. The processing unit digitises pulses received, performs pulse-processing, de-interleaving and multi-path analysis before emitter processing is performed. The following process is performed on the detected pulses:

For each pulse:

- o Convert pulse series to complex form
- o Measure Pulse peak amplitude and average amplitude
- o Measure Direction of Arrival (DOA) based on amplitude difference and phase difference in the three channels
- o Measure Pulse Width (the duration of the pulse)
- o Measure Carrier frequency (corrected according to sub-band detectors)
- o Measure Time of Arrival (TOA)
- o Insert pulses into frequency / DOA histogram

After detection of a predetermined number of pulses or upon reaching a predetermined time limit perform:

- o De-interleaving (identifying which pulses come from the same emitter):
    - Based on frequency/ DOA histogram
- o Perform emitter analysis:
    - Improve DOA measurement by averaging

- Perform echo-recognition by identifying "same" emitter in different directions
- Perform emitter antenna analysis (rotation speed and beam width) based on pulse amplitudes

o Perform emitter classification based on all emitter parameters (excluding DOA)

o Perform emitter recognition based on all emitter parameters (excluding DOA) and sampled pulse waveform compared to emitter library.

If multiple ESM-sensors observes the same area, DOA information from neighbouring ESM-sensors to triangulate in order to find emitter position

At this stage, data may be displayed locally or set to the network for sensor fusion with other sensors. If multiple ESM sensors are connected in a network, local sensor fusion may be performed to provide target positioning. In addition emitter recognition analysis is performed using either a local or network based emitter database. Figure 4 shows the use of multiple ESM-receivers for emitter position determination. A common emitter database (shown as a green oval on shore) is used to convey emitter information from one ESM-receiver to another.

Emitter database maintenance is envisioned integrated with the ESM system. Whenever a new emitter is encountered, the emitter must be identified by other means, but the data is stored for recognition purposes.

The Processing Unit controls the Antenna, Receiver and Navigation unit with respect to frequency coverage. During battery operation, a several non-continuous operation modes may be specified in order to expand battery life.

The processing unit is contained in a single unit with integrated batteries in man-portable mode or rack mounted in platform installation.

Pulse processing algorithm

The processing system receives pulse signal from the radio head. The pulses are digitized in the sampler system such that each pulse is stored as 3 series of samples for each pulse, one series for each channel. In order to determine the pulse parameters, each pulse data series is analyzed with the following algorithm:

- Perform real to complex FFT (Fast Fourier Transform) for all 3 series
- Determine carrier frequency:
  - Locate peak power in the series ($n_{\max}$), see Figure 7.
  - Calculate carrier frequency: $f_c \approx \frac{n_{\max}}{N} f_s + f_{chan}$ where N is number of samples in series f_s is sampling frequency and f_{chan} is the frequency offset of the radio channel (received from the radio head)

- Perform complex inverse FFT (The samples are now complex, and the series length is halved)
- Scan series and determine peak power ($P_{\max}$) for each channel and compute -3dB level: $P_{3dB} = P_{\max}/2$
- Scan series and locate -3dB crossings, calculate 3dB pulse width (see Figure 8)
- Calculate time of arrival as data series start time + offset to first 3dB crossing
- Estimate direction of arrival from pulse series from peak amplitudes:
- Center channel (Ch_0) has maximum power (from radio head)
- Calculate DOA from predetermined antenna lobe calibration function: $DOA = g(P_{-1}, P_0, P_1)$ see Figure 9.

- o Insert pulse with parameters into 2-dimensional histogram, indexed by carrier frequency and direction of arrival.

In summary, the process of finding the direction to a radar emitter includes three steps:

1. The detectors in the IF channels are used to decide if a given signal is received by a front or rear antenna.

2. A comparison between the signal amplitudes in the IF cahnnels, together with the antenna characteristics (Fig. 9) is used to get a coarse estimate of the direction to the emitter.

3. A phase-comparison between the channels is used to get the direction with full accuracy. Step 2 above is needed as a preparatory step, as the phase-comparison is ambigous.

Emitter processing algorithm

After detection and processing of a predetermined number of pulses (or upon reaching a predetermined time limit), a number of pulses from the observed emitters have been analysed and entered into the histogram. An example with two emitters i shown in Figure 10.

In order to de-interleave pulses (sort pulses by emitter), pulses are extracted from the DOA/frequency histogram, starting with the histogram cell with largest pulse count. In the above axample, 3 "emitters" would be extracted, namely pulses from emitter #1, pulses from emitter #3 and fimally pulses from emitter #1 reflected off a reflector (hillside, building etc). Each "emitter" is analyzed according to:

- o Calculate average and standard deviation of all pulse parameters except pulse amplitude
- o Perform Emitter antenna analysis (see Figure 11):

  - Measure time between antenna main lobe passings (time from local maximum to local maximum)
  - Measure antenna beam width (same principle as measuring pulse width)
- Perform emitter PRI analysis
  - Measure time from pulse to pulse and calculate average
  - Optionally: perform analysis of PRI variation (pattern recognition)

After emitter parameter estimation, the directions to and other parameters to all emitters are known. The list also includes "emitters" that are actually copies of other emitters due to reflections off diferent surfaces. These artifacts have the same parameters as the originating emitter except Direction of arrival. In order to determine which emitter is the original the following analysis is performed:

- Compare peak amplitude. The artifact will most often have lower amplitude than the correct emitter
- Compare standard deviations of pulse parameters. The artifact will have larger standard deviations

The emitters are now analyzed and the direction of arrival, pulse parameters and emitter characteristics have been determined.

Emitter position determination using multiple POS sensors

Each sensor analyze pulses from the observed emitters. When emitter analysis is complete, the emitter parameters are sent to any neighbouring POS sensors by data-network.

Upon reception of emitter parameters from a neighbouring POS sensor, this emitter is compared to all of the locally

detected emitters (using all parameters except DOA). When a match is found, the position is determined by triangulation (position of each POS sensor is known, DOA to the emitter from each POS sensor has been determined, thus the emitter position may be determined by simple geometry)

Emitter recognition / Emitter database

In order to recognize emitters from previous observations, the emitter parameters are stored in a emitter database. Upon reception of a new emitter, the emitter parameters are compared with the parameters stored in the database. If a match is found, the emitter is assumed to be the same as the one found in the database. If not, the new emitter is stored in the database.

The database may either be stored locally or accessed by data network. Using a networked database provides the ability to share information about new emitters between multiple POS sensor as soon as the new emitter is detected.

Direct conversion embodiment

While the inventive receiver has been described employing a two-stage conversion scheme with an intermediate frequency, and which is the preferred embodiment of the invention at the present state of the art, the concept of the invention has a wider application.

Under certain circumstances, a direct conversion receiver can be preferred. In this version (not shown), the signals from the antenna(s) are split into a number of sub-bands and mixed directly down to baseband, before they are combined in an adder unit. The output from the adder is digitized and processed as in the example described earlier.

Technical Abbreviations

A/D - Analog/Digital

DOA - Direction of Arrival

ESM - Electronic Support Measures

GPS - Global Positioning System

GS/s - GigaSamples per second

IF - Intermediate Frequency

PRI - Pulse Repetition Interval

TOA - Time of Arrival